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# A 3-dimensional ray-trace model for predicting the performance of flashlamp-pumped laser amplifiers

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## ABSTRACT

We have developed a fully three-dimensional model for the performance of flashlamp pumped laser amplifiers. The model uses a reverse ray-trace technique to calculate the pumping of the laser glass by the flashlamp radiation. We have discovered several different methods by which we can speed up the calculation of the gain profile in a amplifier. The model predicts the energy-storage performance of the Beamlet amplifiers to better than 5%. This model will be used in the optimization of the National Ignition Facility (NIF) amplifier design.

**Keywords:** amplifiers, flashlamps, Beamlet, laser, NIF, ray-trace

## 2. DESCRIPTION OF THE MODEL

To predict the gain in an amplifier, we need to model both the pumping and the decay of the inversion. To do this, we must accurately model a number of physical steps that are involved in getting the flashlamp radiation to the laser glass and converting the pump radiation into stored energy, which then decays through both spontaneous and stimulated processes

A number of individual processes are involved in the calculation of the pump term. We use our xenon flashlamp model[1] to predict the optical emission and absorption from the flashlamp plasma, which is a function of both time and wavelength. We use experimentally determined values of the optical absorption of the various glass types in the amplifiers (laser glass, blast shields, lamp envelopes, etc.), which is also a function of wavelength. At each of the dielectric interfaces, we model both the Fresnel reflection and refraction of the flashlamp radiation using the experimentally determined values of the indices of refraction, ignoring dispersion. In addition, if necessary, we split rays at the dielectric interfaces to track both the reflected and refracted radiation. To calculate the silver reflectivity, which is a function of both angle and wavelength, we use the experimentally determined values for the complex index of refraction of pure silver[2], and then correct by a scaling factor of 0.98 to bring the overall reflectivity in line with what is observed for samples of the silver components used in current amplifiers.

The spontaneous decay of the inversion in the laser glass includes both fluorescence and nonradiative relaxation. To model this we use the decay rates and branching ratios determined experimentally by Caird, et al.[3] The stimulated decay, which is a function of both time and position in the slab, is calculated numerically using experimentally determined values for the gain cross section and fluorescence lineshape.

In addition to being accurate, the amplifier model must also be fast enough to analyze many different designs in a time frame short enough to be relevant for the optimization of the NIF laser design. To this end we have chosen to use a reverse ray-tracing algorithm for the calculation of the pumping of the inversion by the flashlamp light. This technique, coupled with several different optimizations, allows us to get an accurate estimate for the gain distribution in an acceptable amount of time.

The reverse ray-trace technique is illustrated schematically in Figure 1. We calculate the source term by tracing rays back from the slab and noting the sources that they sample.

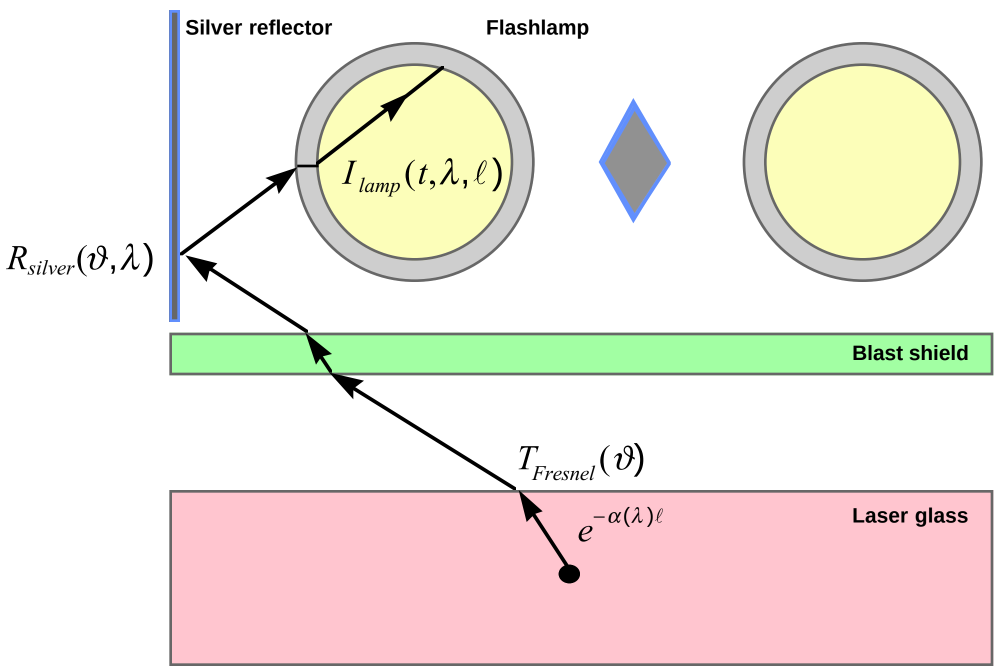


Fig.1. Schematic representation of the reverse ray-trace model. A typically ray is shown, starting at the point of interest in the slab and attenuated on its way back to the flashlamp.

To generate the source term for an individual ray, we convolve the flashlamp output $I_{lamp}$, which is a function of time t, wavelength $\lambda$ and path length traveled in the plasma $\ell$, with the attenuation the ray takes in traveling from the lamp to the point of interest and the glass absorption cross section $\alpha(\lambda)$. The accumulated attenuation includes all losses: the reflectivity of the silver $R_{silver}$ (a function of angle and wavelength), Fresnel reflectivity or transmission at the dielectric interfaces (a function of the angle of incidence), and passive transmission loss when the ray passes through the flashlamp plasma or any of the glass elements in the amplifier. It is important to note that we continue to track the ray backwards through the lamp plasma to see if it intersects other sources; the ray is terminated prematurely in the figure for the sake of clarity.

We have used several techniques to speed up the calculation of the reverse ray-trace:

- Since the calculation of the pump rate at one point in the slab is independent of the calculation for any other point we compute the pump term at different positions in the slab in parallel using a dedicated cluster of workstations. This results in a speed-up factor directly proportional to the number of processors used.

- In principle, the splitting of rays at dielectric interfaces produces an infinitely deep and wide ray "tree". In practice, we eliminate rays from this tree from the calculation once their net attenuation reaches a critical level. This produces a speed-up of a factor of 10 to 20.

- Since the pumping of the laser glass at one point in time is completely independent of the pumping at all other times, we calculate the pump term for all of the relevant times during the flashlamp pulse in parallel using a single ray-trace. This results in a speed-up of a factor of 3 to 5.

- We accelerate the calculation of the pump term by embedding the flashlamp array in an artificial partitioned box, which encloses the complicated array elements in a set of simple rectangular parallelepipeds. This speeds up the calculation by about a factor of 3.

- We delay the evaluation of the wavelength-dependent attenuation factors until the ray encounters a flashlamp and the source term for that lamp is calculated. When a ray passes through any of the glasses, we simply note the total length that it has passed through that type of glass, and calculate the exponentials only when necessary. This produces a speed-up of a factor of about 2.

The computer program that implements the reverse ray-trace model was written in C++, using an object-oriented programming technique. The programming language and technique were chosen for the reasons of code maintenance and extensibility. Using this approach, we find that we can add a new element or material to the model in the matter of a few hours.

We used PVM[4], a publicly available subroutine package to parallelize the code so that the calculation of the pump distribution can be calculated in parallel on a number of workstations. We typically carry out the computations on a dedicated cluster of 28 workstations with a combined computational power of about 1 gigaflop. However, the use of PVM as the distribution mechanism would in principle allow us to spread the calculation over an arbitrarily large number of heterogeneous networked computer systems.

## 3. COMPUTATIONAL RESULTS

One added benefit of the reverse ray-trace approach is that it allows us to generate pictures of the pump integrand at any point of interest in the slab. This is a useful tool both for debugging the code and for developing a better understanding of the nature of the integrand itself. In Figure 2. we show a very simple test geometry along with a picture of the integrand as seen from a point in the center of the slab looking directly at the flashlamp plasma. The left and right sides of the box are perfect mirrors. The upper and lower sides are perfect absorbers. Not shown in the figure are the top and bottom of the box, which are silver reflecting planes. The intensity of the image of the pump integrand is proportional to the magnitude of the pump term for a ray along that direction. All of the pump radiation is contained within the TIR angle of the glass air interface. The direct image of the lamp plasma as well as the images of the plasma in the sides and top and bottom reflectors are clearly visible. The magnitude of the pump term falls off toward the outer portion of the image due to the decrease in Fresnel transmission as the rays tend toward grazing incidence.

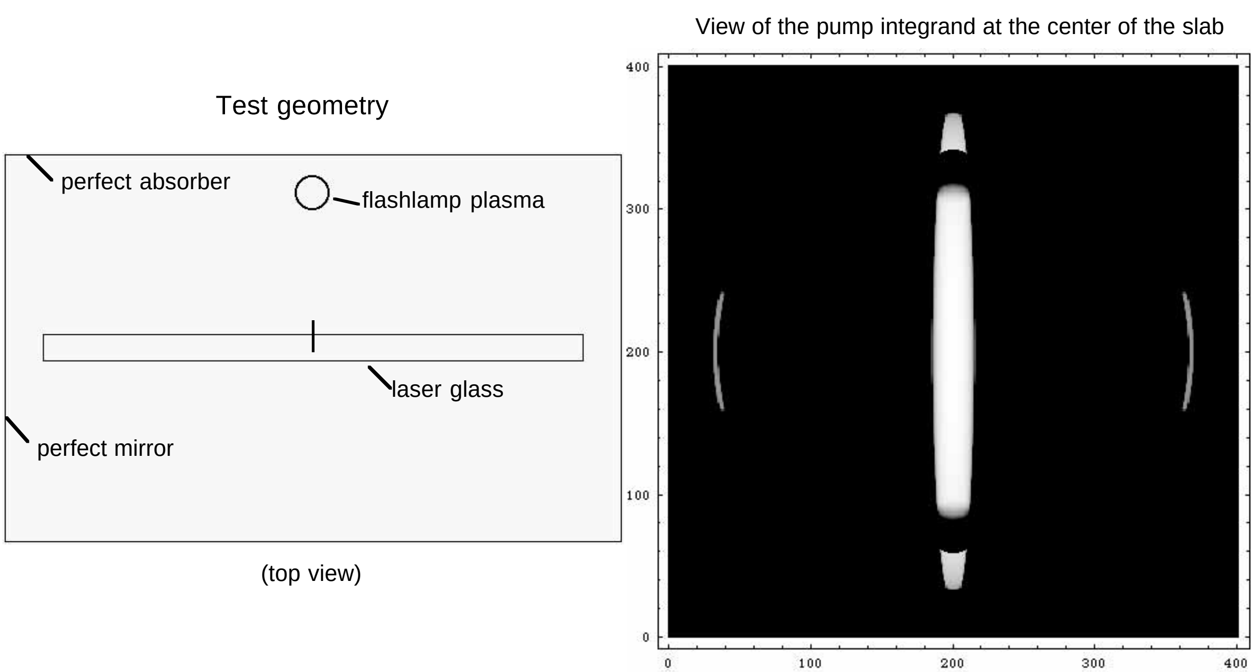


Fig. 2. A simple test geometry for the reverse ray-trace code, along with a picture of the integrand as seen from the center of the slab, looking back at the flashlamp.

The ray-trace geometry for the Beamlet amplifier geometry is presented in Figure 3. All of the optical elements contained in the amplifier are also contained in its model representation. The positions of all of the elements were determined using the engineering drawings, and are accurate to within 0.001 inch. Note that the Beamlet amplifiers have two apertures stacked one on top of the other; the lower aperture is filled with two pieces of architectural glass that absorb approximately as much of the flashlamp radiation as the LG-750 laser glass slab. Not shown in the figure are the silver reflectors that form the top and bottom of the laser aperture. To model the performance of an inner amplifier module, the left and right sides of the box enclosure were modeled as perfect reflectors. The upper and lower sides of the box were modeled as perfect absorbers that prevent any light lost out the sides of the amplifier enclosure from returning to it.

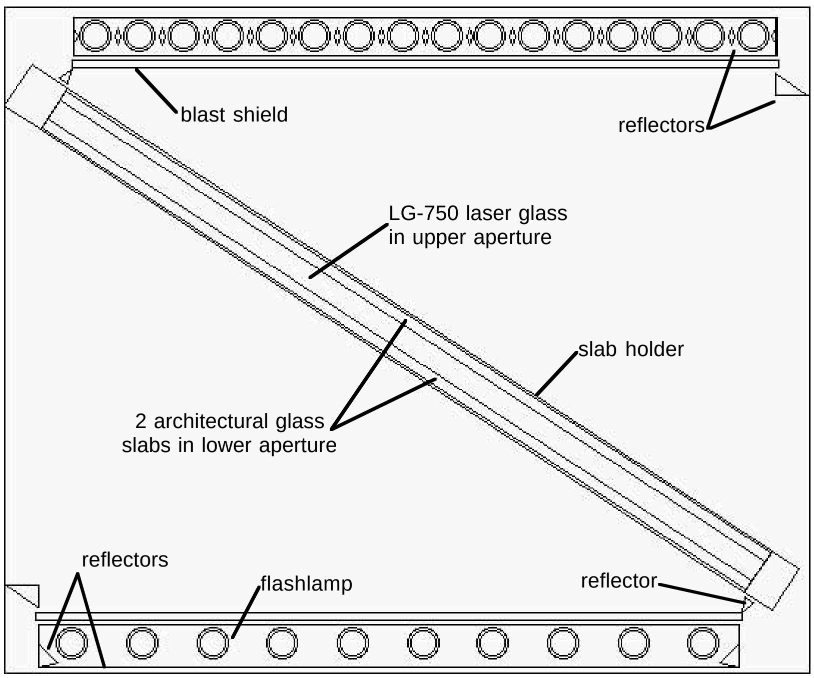


Fig. 3. Top view of the ray-trace geometry for the Beamlet amplifier. Both the upper aperture, containing an LG-750 slab, and the lower aperture, containing two pieces of architectural glass, are shown in projection.

In Figure 4 we show the prediction of the ray-trace calculation for the Beamlet amplifier gain profile, along with the experimentally observed gain distribution for an inner Beamlet amplifier module. The model calculation took about 2 days on our 28-node workstation cluster. The calculated gain profile is in good agreement with that observed experimentally.

## 4. CONCLUSIONS

The good agreement between the model predictions and experiment for this first test of the 3-dimensional ray-trace model is quite encouraging. The time required for a single full simulation is fast enough to answer simple design questions for the NIF amplifiers, and we hope to reduce the run-time further through additional code optimization

The detailed optimization of the NIF laser amplifiers will be carried out using a staged design process. The initial optimization will be done with our $2D^+$ amplifier model. The design will be refined more fully by adjusting the geometry to obtain the best pump profile using the 3-D model at a characteristic lamp input power. The final optimization and verification of the design will be carried out using the full 3-D amplifier model.

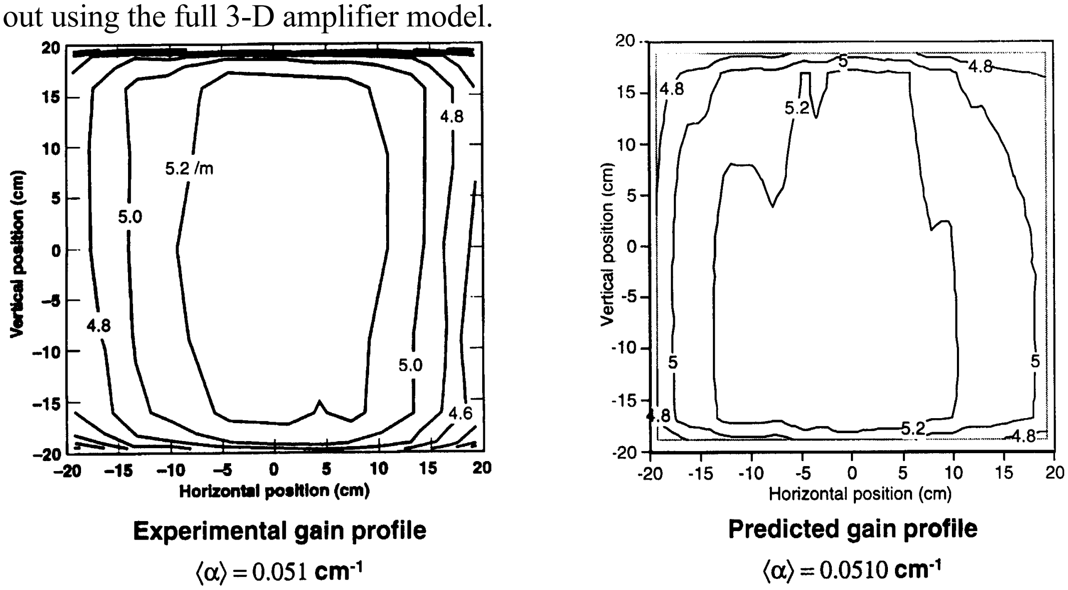


Fig. 4. Comparison of the experimentally observed gain profile in an inner Beamlet amplifier module to that predicted using the 3-dimensional ray-trace model.

## 5. ACKNOWLEDGMENT

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